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An Autonomous Power-Supply Station Based on an Asynchronous Generator with a Phase-Wound Rotor and a Low-Power Frequency Converter

A. B. Vinogradov[a], * **and R. O. Gorelkin**[b], **

[a] *Electrical-Drive Research and Engineering Center "Vektor", Ivanovo, 153021 Russia*
[b] *Ivanovo State Power Engineering University, Ivanovo, 153003 Russia*
**e-mail: vinorg_ab@mail.ru*
***e-mail: roman.gorelkin.96@mail.ru*

Abstract—Today, asynchronous and synchronous generators with double-link full-power frequency converters are the main options for designing highly efficient three-phase voltage sources with an internal combustion engine (ICE) as a prime mover and a variable rotation frequency as a function of the load. It is required to develop and study the efficiency of the use of an autonomous power-supply station with a variable rotation frequency based on a low-power frequency converter in order to provide a decrease in its cost with the potentialities of saving ICE fuel through controlling the frequency depending on the load. The power station and its control system is described both at a structural and at a functional level. The characteristics of the station have been studied by means of computer simulation with the use of the Delphi software package. To assess the potential fuel efficiency of the power station, a multiparameter characteristic of the YaMZ-238 internal combustion engine has been used. A functional diagram of the power station and a block diagram of its control system without using a rotation-frequency sensor are presented. Timing diagrams for the simulation of its operation with the use of an asymmetrical load, as well as its energy characteristics, are presented. The energy characteristics and potential fuel savings of the internal combustion engine when the power station operates with a symmetrical active-inductive load under the conditions of a multiple decrease in the power of the frequency converter with respect to the nominal power of the load. It is shown that, unlike well-known analogues, the developed power station makes it possible to ensure an at least twofold effective rotation-frequency control range of the internal combustion engine while limiting the nominal converter power to 20% of the nominal load power, which provides preconditions for significant fuel savings. The use of the power-supply station in the proposed design makes it possible to reduce its cost by decreasing the power of the converter and increasing the energy efficiency thereof via controlling the ICE rotation frequency with a satisfactory maintenance of accuracy of the output voltage under the conditions of a significantly asymmetric load. The reliability of the results obtained in the course of the studies has been confirmed by means of computer simulation.

Keywords: autonomous power-supply station, asynchronous generator, active rectifier, voltage inverter, internal combustion engine

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INTRODUCTION

Autonomous power-supply stations (APSs) [1–4] are in wide demand as sources of electricity for low- and medium-power facilities that are remote from centralized power networks and as backup electricity sources in the case of a temporary failure in the centralized power supply networks, as well as energy sources for mobile equipment.

Asynchronous or synchronous ac electric machines with a circular rotating field are most often used as generators that convert electromechanical energy. When using an internal combustion engine (ICE) as the prime source of mechanical energy, from the standpoint of providing an increase in the total efficiency of the system and a decrease in its operating costs, it is advisable to use systems that allow operation with a variable ICE rotation frequency. This makes it possible to adjust the rotation frequency of the generator depending on the power of APS loading to provide the operation of the ICE at the maximum fuel efficiency and, thereby, to save fuel under the conditions of highly variable load.

Another important factor consists in the cost of an APS. In terms of this factor, the systems in which only a part of the energy circulating between the prime mover and the load are transmitted through a semiconductor converter have a certain advantage. Based on the combination of the two aforementioned properties, a power station based on an asynchronous generator with a

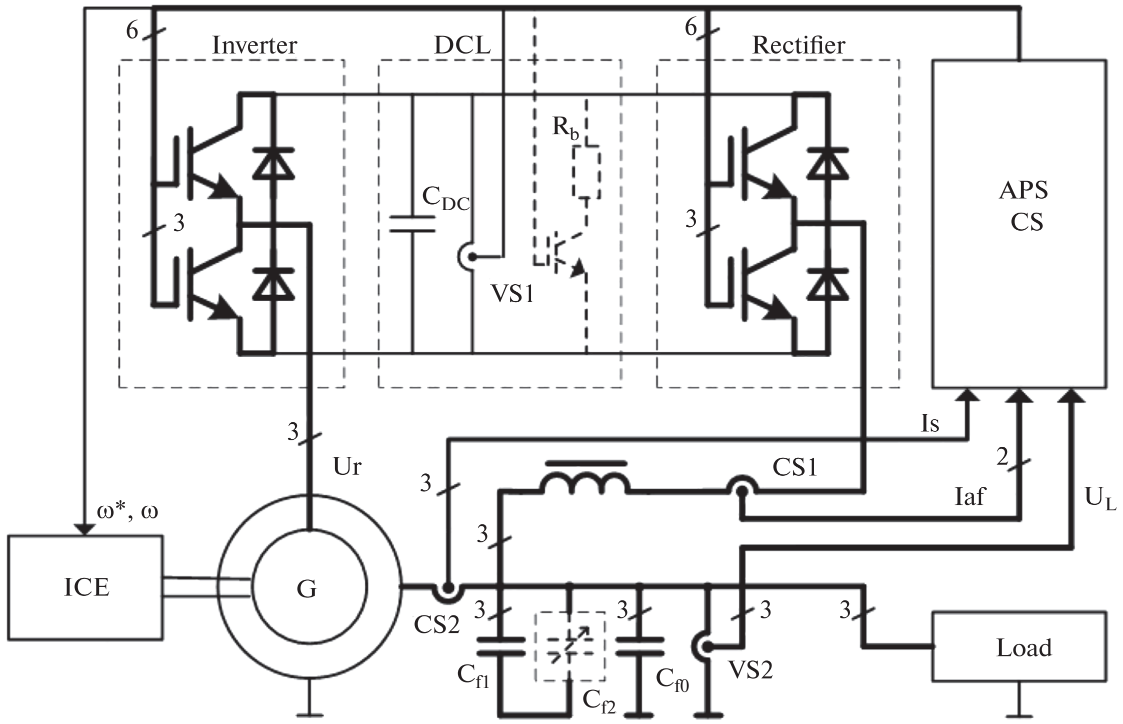

Fig. 1. Functional diagram of the APS.

phase-wound rotor (AGPWR) can be chosen as one of the most appropriate variants for APS designing.

The design of vector control systems for an asynchronous machine with a phase-wound rotor (a doubly fed machine synchronized by an asynchronous generator) has been considered in a significant number of publications [5–11]. In a number of them, the authors consider the issues of control with no rotation-frequency sensor. In this case, systems operating in parallel with the network are most often considered, in particular, in relation to wind turbines, and traditionally little attention is paid to considering the operation of these systems for the case of an asymmetric load. In terms of its design, the control system for the rotor circuit inverter of an APS with an AGPWR significantly differs from the control systems of power stations operating in parallel with the network, both in the set of controlled variables and in the solved problems. In the latter, the voltage and frequency levels are determined by the network, whereas, in the case of autonomous sources, the voltage and frequency stabilizing is provided by the rotor inverter control system.

Below, we consider one of the possible variants for constructing an APS based on an AGDF controlled by a two-link four-quadrant frequency converter based on insulated-gate bipolar transistors (IGBTs) with a PWM (Fig. 1). This variant of APS structure has significant advantages over such other variants as an APS with an uncontrolled rectifier on the side of the AGPWR stator circuit and an APS with four-quadrant thyristor converters, as well as an APS with direct or matrix frequency converters. Compared to the first of the mentioned variants, the variant considered below has a wider range of adjusting the generator rotation frequency both down and up from its nominal value, as well as a better harmonic composition of the output voltage. Compared to the second variant, the harmonic composition characterizing the variant under consideration is significantly better. Compared to the third variant, the considered one has a lower cost, a higher reliability level, and a wider range of perceived loads, which is provided by a smaller number of power switches and the presence of a capacity in the dc link of the converter.

MATERIALS AND METHODS

The functional diagram of APS (Fig. 1) includes a generator (G), driven by an internal combustion engine (ICE); a three-phase bridge active rectifier (AR) based on IGBTs powered by the APS output; a three-phase bridge autonomous voltage inverter (AVI), connected to the AGPWR rotor circuit; a dc link (DCL) containing a capacitive filter and a transistor switch for controlling ballast resistor R_b; an APS control system (APS CS); passive filtration elements; a sensor system consisting of three APS output-voltage sensors (VS2), a dc voltage sensor (VS1), two current sensors at the AR input (DT1), and either two current sensors located at the AVI output, or three current sensors located at the output of the stator circuit of the generator (DT2); and a three-phase four-wire load.

The passive filter elements of the circuit include DCL capacity (CDC); capacity C_{f1} that provides filtering the high-frequency differential components of APS output voltage; capacity C_{f0} that provides filtering both differential and neutral high-frequency components of the output voltage; and variable differentially connected capacity C_{f2}, which allows the reactive power of the system together with C_{f0} and C_{f1} to be balanced taking into account the AGPWR inductances and inductance of the AR input circuit throttle L_f, as well as the inductances of the reactive components of the load. It should be noted that, in the case of restricted ranges of changes in the reactive component of the load, capacity C_{f2} additionally connected to the APS output may be absent.

The functional diagram (Fig. 1) does not show such elements as a 12- (24) V battery connected to the DCL through a cut-off diode, from which the APS is started; a reverse diode in the throttle circuit; protective switching equipment (output suppressors that provide hardware protection against short-term overvoltages alongside with the software protection involved in the APS control system); and a circuit breaker that performs the functions of hardware protection against overloads and short circuits alongside with the corresponding software protection functions.

In addition, the diagram does not show a matching transformer that can be included both in the stator and in the rotor circuits of the generator, whose function consists in matching the operating voltages of the stator and rotor circuits with each other, which provides a minimal cost of the power part of the low-power converter. The functions of this transformer can be performed by the generator itself, the winding data of which are specially coordinated in the course of designing. The ballast resistor and the resistor-controlling switch can be used optionally in the system and, if necessary, can ensure additional protection of the semiconductors in the inverter and rectifier against overvoltage, as well as being able to provide a minimum nominal load in an idle mode of APS.

The block diagram of the APS control system (Fig. 2) includes AR and AVI control systems, as well as an APS state observer (SO) that calculates all the variables necessary for the APS operation using information taken from current and voltage sensors. Information concerning the rotation frequency of the internal combustion engine can be used as the additional information. The two-channel AR vector control system [12] is made based on the principles of subordinate control and includes the controllers of the active (RI_x) and reactive (RI_y) components of the AR input current in an orthogonal coordinate system oriented along the output APS voltage vector.

An external loop with respect to the loop for adjusting the active component of the AR current is represented by the DCL voltage control loop with a $\mathrm{RU}_{\mathrm{DC}}$ controller. The two-channel vector control system of the AVI rotor circuit includes a channel for adjusting output APS voltage (the voltage across a load) with a voltage controller RU_L and a controller of the reactive component of the rotor current RI_d, as well as a channel for adjusting output voltage frequency based on a frequency controller $\mathrm{R}_{\omega\psi}$.

The orientation of all the vector variables of the control system of the rotor circuit AI is carried out in an orthogonal coordinate system rigidly connected with the flux linkage vector of the AGPWR stator. The components of the vectors of the set AVI and AR voltages in orthogonal rotating coordinate systems are restricted in the vector confinement blocks VCB1 and VCB2 taking into account the DCL voltage and, then, are converted in coordinate converters CC1 and CC2 into a natural three-phase coordinate system ABC fixed with respect to the AGPWR stator. Next, in the switch control units (SCUs) of the AVI and SCU of the AR, control pulses are generated for all 12 transistors of the converter according to the sinusoidal law of three-phase PWM formation.

The mathematical description of the aforementioned blocks of the APS control system and the methods for controller synthesis are presented in [12]. The synthesis of controllers of the AVI and AR control system has been carried out in the scope of the theory of subordinate control systems through adjusting the control loops of variable for the optimal processes of the corresponding order taking into account the circuit linearization of these loops and their simplified description in the form of first-order inertial links.

From the standpoint of improving the noise immunity of the sensor system and taking into account the fact that the orientation of AGPWR vector variables is performed according to the stator flux linkage, it is worthwhile to control the generator currents by installing sensors in the stator circuit and to calculate the rotor currents with the use of the state observer according to the system parameters. This additionally provides the ability to calculate and control the neutral wire current in the APS. The set values of the variables at the inputs of the controllers are formed in the setting block, taking into account current restricting functions, loss minimization in the ICE–APS system and uniformity in power distribution between the inverter and the rectifier.

The APS state observer is based on a well-known mathematical description of an asynchronous machine in the form of a system of Park–Gorev differential equations, presented, for example, in [13, 14], which additionally takes into account the nonlinearity of the magnetization circuit and the processes in magnetic core steel, if studies of the energy characteristics of the system are required [12].

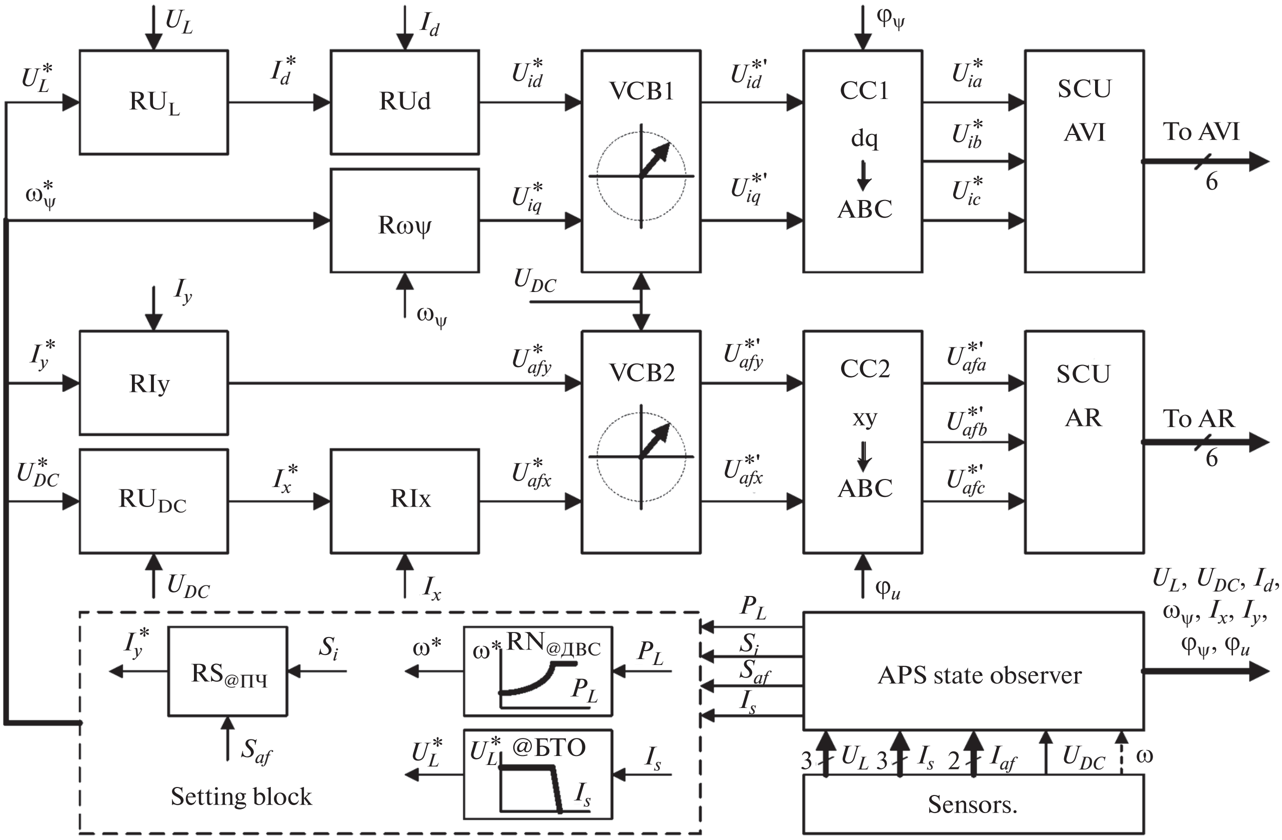

Fig. 2. Block diagram of the APS control system.

The stator flux linkage is assessed based on the vector equation of the generator's stator circuit in an orthogonal coordinate system fixed with respect to the stator according to voltages and currents obtained based on their phase values in the coordinate converter (CC), ABC → αβ. The frequency of the output voltage is determined by the rotation frequency of the generator field calculated as the ratio between the modulo EMF vectors of the stator and the stator flux linkage. The well-known problem of introducing the initial conditions and stabilizing the outputs of integrators that calculate the components of the flux linkage vector is solved using a corrective feedback that compensates for the effect of signal and parametric disturbances exerted on the calculation accuracy of flux and frequency.

By using the mathematical simulation tools, the efficiency of different methods for generating corrective signals has been analyzed. Based on the criterion of minimizing deviations in the estimates of flux linkage and frequency from the introduced testing disturbance into the stator EMF, the correction of integrator outputs through the introduction of negative feedback according to the estimates of the average flux linkage vector components over the period of the fundamental harmonic has been accepted as the base one. The feedback coefficient can be established experimentally from the results of mathematical simulation or in the course of the control system setting up according to the aforementioned criterion.

RESULTS AND DISCUSSION

The APS simulation has been performed in the Delphi environment. In the course of the process simulation in static and dynamic APS operating modes, the algorithms for switching the inverter and rectifier switches, as well as the saturation of the generator magnetic system, have been taken into account. The dynamics of the internal combustion engine were taken into account using a first-order order inertial link based on the data taken from a full-scale experiment.

As the generator, we used an asynchronous machine with a 5AHK250MB4 phase-wound rotor having the following parameters: $U_{s\mathrm{nom}} = 380/220$ V, $I_{s\mathrm{nom}} = 205$ A, $f_{s\mathrm{nom}} = 50$ Hz, efficiency = 94%, $\mathrm{Cos}(\varphi) = 0.87$, $L_{\sigma s} = 0.0002$ H, $L_{\sigma r} = 0.00023$ H, $L_{m0} = 0.0145$ H, $L_{mn} = 0.0076$ H, $R_{s20} = 0.0132\ \Omega$, $R_{r20} = 0.026\ \Omega$, $Z_p = 2$, and $J = 2$ kgm^2. Here, $L_{\sigma s}$, $L_{\sigma r}$, L_{m0}, and L_{mn} are the leakage inductance characterizing the stator and rotor, as well as mutual inductance in an idle mode and in a nominal mode, respectively. When assessing the energy characteristics of APS, we have taken into account steel losses, mechanical losses, and additional losses in the asynchronous machine, as well as the efficiency of the inverter and rectifier, obtained in the course of data processing based on the autonomous bench testing of APS elements.

Figure 3 shows time diagrams of (*a*) output voltages, (*b*) load currents, (*c*) DCL voltages, and (*d*) AGPWR stator currents for phases A and B in the mode of stepwise connection and disconnection of the load of phase A in the range of 0.1–1 with respect to its nominal value.

The integral assessment of the magnitude of distortions caused by an asymmetrical load in the output voltages of APS can be performed based on the relative value of the maximum deviation in the absolute value of the output voltage from its nominal value. In particular, in the steady-state APS operating mode, when one of the phases is loaded with nominal power and the other two with a 10% load, this parameter amounts to 4.8%, which corresponds to the oscillations in the module of the output APS voltage is within +/–15V with respect to its nominal value.

Figure 4a shows total power of the frequency converter S_{fc}, total power of load S_{load}, and the stator current of the generator and the efficiency of APS depending on the rotation frequency of the generator (in relative units). Figure 4b shows the total load power depending on different power coefficients $K_{\text{p}} = 1.0$, 0.9, and 0.8. The dependences have been obtained for the maximum long-term operating modes of an APS with restrictions in the nominal stator current of the generator and in the nominal power of the converters (active rectifier and inverter) confined to 20% of the nominal load power. The nominal APS operating mode, characterized by the nominal values of the converter power and generator current at a symmetrical *RL*-load with power coefficient $K_{\text{p}} = 0.9$, has been accepted as the base one. The absolute values of the parameters of the nominal APS operating mode at the mentioned restrictions are as follows: $N = 1855$ rpm, $S_{\text{load}} = 181$ kVA, $S_{\text{fc}} = 35$ kVA, $I_{\text{s}} = 205$ A, APS efficiency = 94.3%, $R_{\text{load}} = 0.7227\ \Omega$, and $L_{\text{load}} = 1.114$ mH.

The total differential capacity at the APS output ($C_f = C_{f1} + C_{f2} + C_{f0}$) is assumed to be constant. The capacity value has been set in such a way that, in the idle APS mode, it completely supplies the generator with the reactive power required for the generator excitation. This capacity can be calculated according to the following relationship:

$$C_f = I_{m\text{nom}} / \left(2pf_{s\text{nom}}U_{s\text{nom}}\right), \qquad (1)$$

where $I_{m\text{nom}}$ is the nominal current in the AGPWR magnetizing circuit.

In this case, in the idle mode and with a purely active load, the reactive power circulating in the converters is close to zero, whereas their total values of power are mainly determined by the active components that are close to each other within small values of their own losses in the converters. If there is a reactive component of an inductive nature in the APS load, the balance of reactive power already cannot be provided only via the capacity of C_f and so the additional reactive power begins to circulate through the converters and the DCL capacity. In this case, the power minimization for the frequency converter (FC) can be provided by equalizing the total powers of the AR and AVI by means of the controller of FC power (RS_{fc}, see Fig. 2) that generates a setting for the reactive current of the AR.

Optimization of energy parameters for the ICE–APS system taking into account losses in the internal combustion engine has been carried out through adjusting its rotation frequency as a function of the load power using a diesel rotation frequency controller (RN_{inc}) (Fig. 2). The set rotation frequency of the internal combustion engine determined by the controller depending on the current value of the load power is formed according to the characteristics of the maximum fuel efficiency (minimum losses) of the internal combustion engine taking into account the limiting dependences for APS (Fig. 4) and the fact that the own efficiency of the APS is relatively high and insignificantly varies with the rotation frequency. In this case, it is important to match the parameters (rotation frequency and power) of the nominal APS mode with the characteristics of the internal combustion engine. The value of the rotation frequency at which the APS is capable of transmitting maximum power to the load in a long-term mode depends not only on the nominal rotation frequency of the AGPWR, but also on the restriction imposed on the FC power. The latter is chosen at the APS design stage to be consistent with the characteristics of the internal combustion engine.

The efficiency of rotation frequency control for a diesel generator set depending on the APS load can be assessed using the multiparameter characteristic of the internal combustion engine (Fig. 5). In particular, for a diesel engine of YaMZ-238 series with an average load power of 75 kW, the relative excess fuel consumption when operating at a constant rotation frequency of 1850 rpm with respect to the operation in a mode with the maximum fuel intensity at a rotation frequency of 1000 rpm amounts to

$$\delta g = \frac{g_{e\,\text{nom75}} - g_{e\,\text{opt75}}}{g_{e\,\text{opt75}}} = \frac{258 - 214}{214} = 0.206,$$

where $g_{e\text{nom75}}$ and $g_{e\text{opt75}}$ are the specific fuel consumption levels when operating an internal combustion engine with a power of 75 kW at a nominal and an optimal rotation frequency (in terms of fuel efficiency), respectively.

Thus, if the average loading power does not exceed 50% of the nominal power of the internal combustion engine, fuel saving at the expense of adjusting the rotation frequency depending on the load in accordance

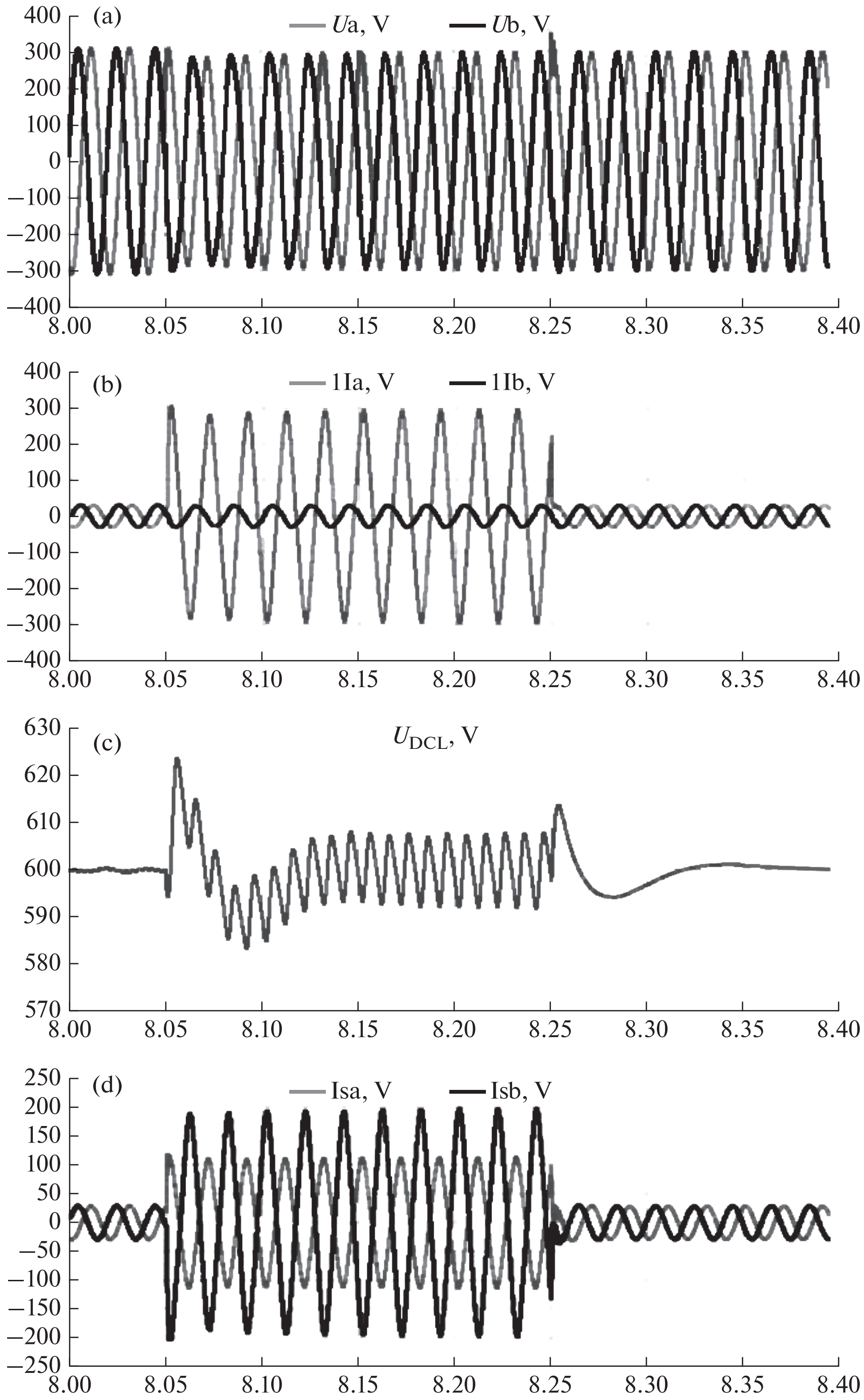

Fig. 3. Timing diagrams for switching on an asymmetrical linear load.

with the maximum fuel efficiency characteristic can amount to 20% compared with operation at a constant rotation frequency corresponding to the nominal power station mode. In the course of long-term APS operation in a low-load mode, the level of fuel saving caused by the rotation-frequency control can be significantly higher.

The APS is protected from current overloads through reducing the output voltage of the AVI in the current-limiting unit (CLU) (Fig. 2). Protection

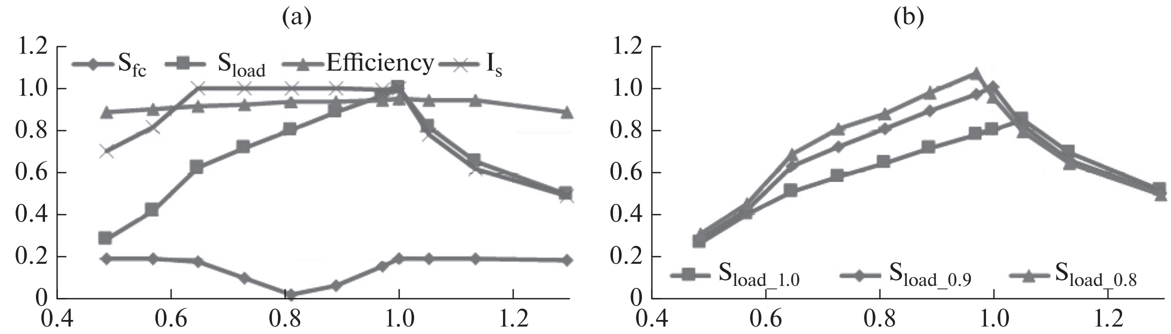

Fig. 4. Energy characteristics of the APS in the case of a linear symmetrical active-inductive loading.

against short-circuit events is provided by a temporary blocking of the power switches of the converter with automatic return to the operating mode when the short circuit ceases.

In the course of the simulation, rational values for all the passive filter elements involved in the APS have been determined. The DCL capacity is chosen according to the condition of limiting the pulsation value at the desired level in the ultimate dynamic and asymmetrical APS operating modes, the inductivity of the input AR throttle is selected according to a given value of high-frequency (at the PWM frequency) pulsations of its input currents. The neutral output capacity, also known as the “minimum differential APS output capacity” (C_{f0}), is chosen according to the desired value of high-frequency pulsations of the output voltage, the total differential output capacity (C_f) is chosen based on the reactive power required to excite the generator.

It should be noted that, in the case of a purely active load and load power coefficients close to unity, the APS satisfactorily operates under the condition of $C_f = C_{f0}$. At the above-mentioned AGPWR parameters and a PWM frequency of 5–10 kHz, the value of this capacity can be relatively small amounting to 20.50 μF. In this case, the reactive power required for the AGPWR excitation is mainly provided by the DCL capacity. However, when the load power coefficient in the APS decreases, self-oscillations are excited, which subsequently lead to inoperability and cause a lack of the established balance in the reactive power of the system. To eliminate this effect, the capacity of C_f should be increased to the value determined by relationship (1).

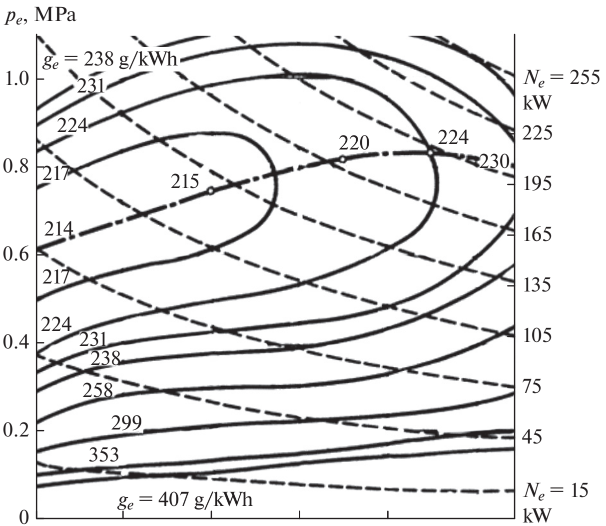

Fig. 5. Multiparameter characteristics of the YaMZ-238 diesel engine: N_e is the diesel power, kW; n is the diesel rotation frequency, rpm; g_e is the specific fuel consumption, g/kW h; p_e is the average effective pressure on the piston, MPa.

CONCLUSIONS

Analysis of the data obtained based on the performed studies makes it possible to draw the following conclusions confirming the fact that the set goal has been achieved:

— the developed APS based on an AGPWR with a low-power frequency converter provides an opportunity for constructing a highly efficient and relatively inexpensive three-phase alternating voltage source capable of operating in a wide range of loads, including a source with a low power coefficient and under the conditions of the maximum asymmetry of phases, the power of which is many times higher than the installed power of the frequency converter;

— when the nominal power of the converter is restricted to 20% of the nominal load power, the effective rotation-frequency control range of the internal combustion engine, which provides an increase in the energy efficiency of the APS and, as a consequence, a significant fuel saving, at least a twofold one. If necessary, this range can be expanded owing to increasing power, i.e. at the expense of the cost of the APS converter part.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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